# THE SEDIMENTOLOGY OF HYDROCARBON RESERVOIR ROCKS IN INDONESIA, A CASE STUDY FROM THE NORTH SUMATRA BASIN

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## ABSTRACT

*The North Sumatra backarc basin has been an important hydrocarbon province for more than 100 yrs. High grade light oils and condensates have been produced from sandstone reservoirs in the deltaic Keutapang Formation and the shallow marine sandstones of the Baong Formation. The basin has a high geothermal gradient, which is in the order of 40-50 C/km (compared to 30/km in the North Sea or Gulf Coast areas) and is a result of its position close to the subducting margin of the Indian Ocean Plate.*

*This presentation includes a general account and discussion of the methods of sedimentological core analysis currently practiced in LEMIGAS, followed by a case history from the North Sumatra Basin using data derived from cores made available by Pertamina Unit 1. Preliminary work has concentrated on the marine sandstones of the Besitang River Sand Member (BRSM), and particularly on the spectacular chlorite cements found in these units. The BRSM sandstones are very fine to fine-grained, grey-green sandstones which in some intervals are clean, massive, structurelees sequences and in others are strongly bioturbated and muddy. Occasional flecking by dark carbonaceus particles commonly occurs and some muddy cross-laminated and cross-bedded intervals are also present. Thin calcite and ferroan calcite-cemented intervals occur at several horizons. Glauconite is present in all the sandstones examined. The general lithology, sedimentary structures, presence of glauconite and bioclastic material are consistent with deposition in a shallow marine environment which, based on seismic evidence, was contemporaneous with, and lay seaward of, a complex of northeastward prograding deltaic lobes.*

*The sandstones are moderately well sorted lithic subarkoses with grainstone textures. The dominant framework grains are monocrystalline quartz, feldspars and rock fragments. Both potassic and sodic feldpars are commonly present and show extensive dissolution. Skeletal feldspars with associated fractured remnant clay coatings often occupy oversized pore spaces. Igneous and metasedimentary grain-types dominate the lithic component. Bioclastic debris is variable in abundance, usually occurring as indeterminate calcitic skeletal debris or foraminiferal tests. Well rounded glauconite grains are common often showing signs of both alteration and dissolution. Authigenic cements present include silica overgrowths and pervasive grain coating chlorite. The chlorite clay coatings are up to 10 microns in thicknees. Occasionally pore-filling chlorite cements are also present. The carbonate cemented sandstones have calcite or ferroan calcite cements. The carbonate cements are clearly seen to post-date the chlorite grains coatings.*

## I. INTRODUCTION

Indonesia as a major oil producing nation has a continuously expanding sedimentological database provided through exploration and field development activities by the state oil company PERTAMINA and through exploration and production sharing contracts with most of the worlds major oil companies now operating in the archipelago. LEMIGAS as a research

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arm of the Indonesian government is attempting, on a limited scale as yet, to assess and understand the widespread sedimentological variations occurring in the many different hydrocarbon basins and reservoirs of the archipelago.

The following presentation includes a general account of the methods used by Lemigas in core analysis sedimentological studies, together with a discussion of the relevance of the techniques, followed by the presentation of a case history using data from the Mid-Late Miocene sandstone reservoir rocks of the North Sumatra Basin. The commercial in confidence nature of some of this work has meant that the actual well locations from which samples were provided by Pertamina Unit I have been omitted.

The Tertiary sandstone reservoirs in the North Sumatra back-arc basin have been producing hydrocarbons for over 100 yrs (Fig. 1). Recent exploration in the area has concentrated in part on prospects in shallow marine sand stone reservoirs which sedimentological and seismic evidence suggest lie seaward of the main prograding deltaic sandstone reservoir sequences of the Keutapang Formation. The stratigraphy and nomenclatures used in the basin are complicated by these extensive lateral facies changes. The most recent stratigraphy to take account of these facies changes is summarised in Fig.2 (Kirby et al 1989). Middle-Late Miocene marine sandstones sequences form a potential reservoir - the Besitang River Sandstone Member (BRSM). A number of cored sequences from this unit have been made available by Pertamina Unit I for examination in the present study. This study forms part of the continuing Indonesian Hydrocarbon Basin Assessment project being conducted jointly by the British Geological Survey, University of London and LEMIGAS and sponsored by the British Government's Overseas Development Administration (ODA).

## II. CORE ANALYSIS METHODS

### *II.1. General*

Core analysis studies of reservoir rocks undertaken by LEMIGAS aim to provide as much information as possible concerning the basic lithologies present, mineralogical composition of framework grains, matrix and cements and depositional environment. Overall reservoir quality in terms of porosity and permeability trends are also assessed and advice concerning potential reservoir engineering problems offered. In addition data from these studies enables Lemigas to improve their own regional database on the sedimentology of the Indonesian hydrocarbon basins.

Petrological studies of cored sequences form the basis of a sedimentological study and, particularly in a humid tropical climate like that of Indonesia where field outcrops are generally heavily weathered and samples use less for most diagenetic work, rely on access to fresh rock material from conventional and sidewall cores.

A core analysis study begins with the preparation of a detailed sedimentological log of each core, followed by grain-size, thin section studies (to determine mineralogy and porosity characteristics) and X-ray diffraction analysis of both bulk rock and clay mineral fraction compositions. Scanning Electron Microscope (including Energy Dispersive X- ray Analysis) studies are also routinely carried out to determine reservoir poroperm characteristics and mineralogy. Increasingly reservoir-wide studies and correlations now rely on the calibration of data from these core studies to downhole geophysical log responses.

### *II.2. Core Logging-Lithology and Sedimentary Structures*

Initial core studies assess the gross lithological character of the potential reservoir. Questions to be con sidered at this stage for sandstone reservoirs include the following : how thick are the porous sandstone units present; are the sands friable or well cemented; what are the cements present and how do they effect porosity and permeability; are there impermeable clay clasts, lenses or laminae present which may disrupt permeability; is there any evidence for possible structural controls on porosity and permeability in the reservoir such as fractures, joints or faults?

Finally a preliminary interpretation of the depositional environment can be made from the sedimentary structures and any fossils present. This may include speculations, at this stage, as to the lateral extent of the porous horizons within the sequence i.e. are they sinuous channel fills or laterally extensive sheet-like sand bodies. Refinement of these models comes with further drilling and logging of the reservoir sequence.

A good core log is the basis on which many subsequent decisions concerning completion, production and development of a well or reservoir are made.

### II.2.1. Besitang River Sandstone Member

The Besitang River Sand Member in the cored sections examined comprises very fine to fine-grained, grey-green sandstones that are considered to be typical representatives of the many thin marine sandstone units in the area. The sandstones in some intervals are clean, massive, structure less sequences, in others are strongly bioturbated and muddy. Occasional flecking by dark carbonaceous particles commonly occurs and some muddy cross-laminated and cross- bedded intervals are also present. Thin carbonate-cemented intervals occur at several horizons. Glauconite is present in all the sandstones examined.

The general lithology, sedimentary structures, presence of glauconite and bioclastic material are consistent with deposition in a shallow marine environment as sheet-like bodies which, based on seismic evidence, were contemporaneous with, and lay seaward of, a complex of north eastward prograding deltaic lobes.

## III. MINERALOGY AND TEXTURES

### *III.1. Thin Section Analysis*

Thin section analysis of selected samples from the cored sequence, from both potential reservoir and non- reservoir units, provides valuable information on the small scale changes occurring in a rock sequence and is the primary method of assessing its reservoir potential. Initial examination of the rock section establishes its basic mineralogy, which is used conveniently to classify the rock (i.e to give it a name) and to determine its grain size and grain sorting characteristics. Subsequently a detailed diagenetic history of the rock (i.e. a study of the physical and chemical changes which have occurred in the rock since its deposition) may be determined.

Most sandstone rock classifications are based on the relative proportions and composition of the primary frame work grains of the rock, usually quartz, feldspar and lithic (or rock) fragments. It is around these framework grains that the primary depositional porosity develops. LEMIGAS follow the classifications of Folk (1974),Mcbride (1963). Sorting of the rock components is a particularly important characteristic. Well-sorted sandstones, i.e. those with framework grains of roughly similar shape and size, show much higher primary depositional porosities than poorly sorted ones, irrespective of the mean grain size of the rock. Determination of the mineralogical composition of a rock is important because of the different ways in which its varied mineral constituents react to changes in either (or both) physical or chemical environments (diagenesis), as a provenance indicator and in order to calibrate down hole geophysical log responses (particularly the nuclear logs).

As burial of the sediment proceeds minerals initially stable at surface pressures and temperatures become unstable and more reactive i.e. diagenesis begins to occur. In a sandstone the ratio of chemically stable quartz grains (generally the dominant framework grain constituent) to the more chemically reactive feldspars and lithic fragments is of particular interest. There is a substantial body of evidence that shows that feldspars in particular are very sensitive to such changes in the geochemical environment. Corrosive reactions between feldspars and pore fluids often result in partial or even complete dissolution of the grains to form secondary pore spaces (Plate 5).

Other framework grains (e.g. micas and rock fragments) may undergo extensive physical deformation or breakdown during mechanical compaction of the sediment. In the extreme cases known, ductile rock or mineral grains may be so severely squeezed that they form a pseudo-matrix to the rock destroying porosity (Plate 8).

In addition to framework grains, the potential reservoir rock contains intergranular cements or matrix and pore space. Thin section analysis is used to assess the type and extent of cements present (e.g. whether they are silica, carbonate or clay mineral cements) and is also increasingly used in diagenetic studies to try and determine the relative timing of cementation phases in relation to hydrocarbon emplacement. Cementation has perhaps the biggest destructive effect on the reservoir potential of a rock (Plate 4). It is important not only to recognise that such cements are present but also to document their composition so that subsequent physical/ chemical treatment of a reservoir to increase or improve oil production do not, by damaging the reservoir porosity or permeability, have the opposite effect on production levels.

Porosity and permeability studies of thin sections are enhanced by the use of dyed resin impregnations. Commonly the rocks are impregnated, before thin sectioning, with a blue resin to maintain and better identify pore space within the rock (Plate 1). Two types of pore space are recognised from thin section studies, a primary porosity developed at the time of deposition and a secondary porosity resulting from modifications, usually by dissolution, to framework grains and/or matrix during subsequent burial diagenesis. In sandstone reservoirs primary depositional porosity is of greatest importance and secondary porosity development is usually only of moderate significance (Plate 6).

### III.1.1. Besitang River Sand Member

In thin section these sandstones may be classified as lithic subarkoses. They are moderately sorted, with grainstone textures. Pressure solution fabrics such as grain welding are rarely observed. Porosities are in general good but permeability has been affected by authigenic clay cementation (Plate 1) and locally by carbonate cements (Plate 2). The dominant framework grains are quartz, feldspar and rock fragments. The quartz grains present are monocrystalline varieties often showing extensive strain features including undulose extinction. Other less common grain constituents include glauconite as pellets and foraminiferal test infills, pyrite framboids, carbonaceous fragments, foraminiferal tests and indeterminate bioclastic fragments.

Both potash-rich and sodic feldspars are commonly present. The sodic feldspars almost always show extensive dissolution along cleavage planes and appear to be the most unstable of the two feldspar types (Plates 5 & 7) . The K-feldspars show more limited dissolution. Feldspar dissolution has produced moderately extensive secondary honeycomb-porosity. In more severe cases only skeletal feldspar or fractured remnant clay coatings remain to occupy oversized pore spaces (Plate 6).

A wide variety of rock fragment types are present with metasedimentary rock fragments dominating the lithic component.

Bioclastic debris is variable in abundance, usually occurring as calcitic skeletal fragments. Foraminiferal tests are particularly common either with open intraskeletal porosity in the test chambers or infilled with fine green clay material (?glauconite/chlorite) or by a later ferroan calcite cement (Plate 7). The foraminiferal tests are largely uncrushed.

Glauconite pellets are common in many of the thin sections examined. The pellets are well rounded often have well developed chlorite coatings and show signs of both alteration and dissolution (Plate 3).

Authigenic cements present include minor silica over growths and authigenic chlorite grain coatings. The development of quartz overgrowths in the samples examined is very variable. In some sections pore space is patchily occluded by euhedral quartz overgrowths and in others the overgrowths appear to be closely related to the extent and ? thickness of the earlier chlorite rims. Where the chlorite rims are thick (10 microns) and well developed then quartz overgrowths are rare. Alternatively where the chlorite coatings are thin and discontinuous extensive quartz overgrowth has occurred, with euhedral quartz crystals enveloping earlier isolated chlorite crystals and almost completely occluding pore space.

In many of the sandstone samples examined there is an almost pervasive development of chlorite cements (Plate 1). These radial chlorite pore-lining/grain-coatings show a typical honeycomb morphology under the SEM which on closer inspection comprises numerous interlocking crystal platelets arranged perpendicular to the host grain surface (Plate 3). The clay coatings are up to 10 microns in thickness, but even when very well developed fail to plug completely the pore spaces. The chlorite coatings cover grains of many different compositions. Occasionally pore-filling chlorite cements are also noted. The chlorite cements are present both within and outside the oil-bearing intervals of the reservoir and therefore clearly predate the generation and migration of hydrocarbons in the basin. If a calculation is made removing the effects of the chlorite cements the porosities were probably originally up to 55% greater. This fact together with the extensive alteration or dissolution of unstable minerals and high proportion of secondary oversized pores points to an early invasion of the reservoir by corrosive (alkaline) pore fluids.

The carbonate cemented sandstones intervals which occur are considered to be of diagenetic origin. Much of the patchy cement is calcitic but occasionally a more pervasive ferroan calcite cement is present. Both varieties of calcite cement are clearly seen to post-date the chlorite grain coatings (Plate 4). Ferroan calcite cement is also seen to infill the cavities in some leached sodic feldspar grains in a number of sections, placing constraints on its time of precipitation (Plate 7).

### *III.2. Scanning Electron Microscope*

In recent years the information provided by thin section studies of reservoir rocks has been complimented by the use of new techniques. Principal among these in the study of reservoir rocks is the use of the Scanning Electron Microscope (SEM.). The SEM provides very high magnification images from rock chips and allows much more detailed analysis of rock mineralogy (using the Energy Dispersive X-Ray Analyser) and porosity/permeability development and destruction.

In sandstone reservoirs during diagenesis a number of authigenic cements, for example, may precipitate in the pore systems modifying or destroying the quality of the reservoir. Using the SEM. the distribution and development of these cements has become much better understood. These cements include silica cements as quartz overgrowths on detrital framework grains, a wide range of pore-filling carbonate cements including calcite (ferroan and non-ferroan varieties), dolomite and siderite and clay mineral cements. Authigenic clay mineral cements are commonly a major factor in porosity and permeability destruction and need to be described with care. Five common pore filling or pore lining authigenic clay mineral cements have been recognised, kaolinite, illite, smectite, smectite-illite and chlorite. Each of these cements shows very distinctive physical crystal morphologies under the SEM. Determining the presence and composition of these cements is of particular importance as they affect reservoir quality and production processes in different ways. Loosely bonded kaolinite crystal plates and fragile fibrous illite are easily transported during fluid flow and may block pore throats reducing production levels. Smectitic clays alternatively tend to take up water in their structure and swell in size within pore throats and pore spaces. The large surface area of these authigenic clays, a result of their microporous structure, also means that they raise the irreducible water content which in turn affects resistivity log responses used in the calculation of fluid saturation levels.

The Scanning Electron Microscope, in particular, has enabled the study of the porosity and permeability of a rock to be carried out in much greater detail. The three dimensional imaging of both framework grains, pore space and the minerals that occupy the pore spaces as matrix or cement allows more precise assessment of reservoir quality and allows better informed decisions to be made concerning any subsequent chemical or physical treatments that may be necessary to stimulate hydrocarbon production from a reservoir.

### II.2.1. Besitang River Sand Member

Extensive SEM studies of the BRSM samples confirm that in most cases well developed authigenic chlorite cements dominate (Plates 9-18). Occasionally euhedral quartz over growths are also common. The chlorite cements typically comprise a 10 micron thick, box-work or honeycomb of crystal platelets lying perpendicular to the host grain (Plates 9 & 12). Occasional chlorite "rosettes" are also seen. The chlorite cements significantly reduce the primary porosity but rarely occlude it completely. Extensive micro porosity is apparent within the box-work structure but connectivity may be poor. Chlorite cementation appears to damage several permeability in the samples as few pore throats remain open (Plate 14).

### *III.3. X-Ray Diffraction Studies*

More precise information about the mineralogical composition of a rock is often necessary to improve the calibration between geophysical log responses and mineralogical composition or before certain treatments to the reservoir are carried out. Geophysical logs respond either to the minerals present in the rocks or to the pore fluids contained within the rock and it is essential to make an accurate calibration between mineralogy and log response to avoid misinterpretation of the fluid responses. Such information is usually most readily obtained from X-Ray Diffraction Analysis (XRD). Initially the bulk mineralogy is determined from a powdered sample and then separation of particular mineral fractions e.g. the clay minerals can be made for further analysis. XRD studies are routinely carried out for most core studies. In this way, for example, unusual peaks on log responses, sometimes a result of localised mineral concentrations, can be analysed.

### III.3.1. Besitang River Sand Member

The limited XRD studies so far carried out on the BRSM samples confirm the bulk mineralogical composition determined from thin section analysis and also show that the chlorite cements present are relatively pure in composition. Further, more detailed analysis of the composition of the chlorite cements will be undertaken in the near future using a microprobe system.

## IV. DIAGENESIS

### *IV.1. General*

Studies of the diagenetic history of a reservoir are a means of establishing the controls on reservoir quality. They can, for example, enable the timing of emplacement of hydrocarbons into a reservoir to be determined because most diagenetic events cease after emplacement. Diagenetic reactions may be related to physico-chemical conditions in the original depositional environment (early diagenetic) or may develop during its subsequent burial history (late diagenetic). Diagenetic reactions appear to be the source not only of the inorganic cements in the reservoir but are also responsible for hydrocarbon generation in a basin. Diagenesis may destroy porosity and permeabilty of a reservoir by the precipitation of cements or enhance reservoir quality by the leaching of framework grains or matrix.

### *IV.2. Besitang River Sand Member*

A preliminary diagenetic history of the BRSM sequence is :

i) early diagenetic near-seabed formation of glauconite as pellets and foraminiferal test infills
ii) mechanical compaction, evidenced by brittle fracture or ductile deformation of micas, some foraminiferal tests and glauconite pellets
iii) early patchy or localised calcite cementation in some intervals
iv) growth of authigenic chlorite grain coating cements
v) limited quartz overgrowth (very occasionally quite extensive) and further carbonate cementation
vi) leaching of unstable silicate grains (both K- and Na- feldspars and ?glauconite)
vii) locally extensive late ferroan-calcite cementation

(perhaps related to uplift of the reservoir sequence)

viii) further fabric compaction and collapse of some chlorite rims which now occur as isolated fragments in oversized pores (perhaps related to uplift and tec tonism)

ix) continuing quartz overgrowth development, enveloping some chlorite crystals

x) hydrocarbon emplacement-cessation of diagenesis

### *IV.3. Origin of the Chlorite Cement*

The origin of the chlorite cements in the North Sumatra Basin is of particular interest. Two main authigenic cements are known from the Mid-Upper Miocene sandstone sequences of the basin. In the marine sandstone units such as the BRSM discussed above chlorite predominates while in the fluvio-deltaic sandstones (Keutapang Formation) kaolinite cements dominate with subordinate chlorite. At first sight this appears to indicate a close relationship between the genesis of the cements and the original depositional environment of the sandstones. However, this may only be partly true.

It has been suggested that kaolinite genesis is related to freshwater flushing by slightly acidic meteoric waters (e.g. Bjorlyke 1983). The flushing process leaches feldspars and other susceptible grains (notably volcanic types) to provide a source of Al and Si which precipitate finally as kaolinite. Marine sandstones unless uplifted and subjected to freshwater flushing would therefore be expected to show limited kaolinite development. Again at first sight in the NSB this simple model appears to work as many of the shallow marine sandstones like the BRSM commonly have chlorite cements. While this model accounts for the possible genesis of kaolinite it necessitates an additional explanation for the origin of the chlorite cements.

An alternative explanation for the source of the necessary Al and Si and other ionic species for both kaolinite and chlorite genesis, however, has been proposed. In this model the necessary ions are derived from fluids expelled as a result of reactions occurring within adjacent or interbedded mudstone intervals during burial compaction (e.g. Curtis 1978, 1983). These reactions either involve any organic material present to produce organic acid solutions, in part promoting further grain dissolution to take place, or may be dehydration reactions where water is expelled from the crystal lattice of some clay minerals, such as the illite-smectite group, carrying with it various donor ionic species (e.g. Boles and Franks 1979). Kingstone (1978) suggested that the temperature controlled smectite to illite conversion reactions occur in the basin between 101-143$^{\circ}$C which using geothermal gradients between 40- 50$^{\circ}$C/km for the basin suggests conversion can begin at depths as shallow as 1.5km. This compares with a depth limit of 2.5km in the Gulf Coast.

The formation and precipitation of kaolinite involves extra Si and Al ions whereas chlorite formation requires Al, Si and additionally Fe, Mg ions. Some chlorite cements have been reported to form during early diagenesis and others during deep burial diagenesis. With an increase in depth of burial kaolinite has been shown to transform to chlorite by the addition of Fe and Mg derived from smectite dehydration reactions. As noted above the high geothermal gradient in the NSB suggests that such reactions may well occur in this basin at much shallower depths. In the BRSM the presence of glauconite, ferroan and magnesium carbonate cements suggests there has been no short age of Fe and Mg ions in the pore fluid system since deposition.

What then was the source of the Mg and Fe for the chlorite cements? At this stage we can only say that the dissolution of feldspars, glauconite and rock fragments was probably not a primary source of ions in the marine sandstones as the well developed chlorite fringes on these grains can be clearly shown to predate the dissolution phase. It seems that the more likely source of ions was the reactions occurring in the adjacent and enclosing marine mudstone sequences, particularly as the thin marine sandstones form a very minor proportion of the basin fill as a whole. Mudstone sequences dominate the basin fill and the thin sandstone units provide the only porous zone into and through which expelled pore waters (and for that matter hydrocarbons) can migrate.

Further work is still needed to establish if there is a regional pattern of authigenic clay cementation in the North Sumatra Basin and to determine whether such a pattern, if it exists, is related to original depositional setting or is a diagenetic overprint unrelated to depositional environment.

### *IV.4. Provenance of the Sandstones*

An aspect of particular interest in the sandstones of the NSB, and in Indonesia in general, is their provenance. Seismic evidence strongly suggests that the deltaic sandstones of the Keutapang Formation are derived from the Barisan area as prograding sediment wedges. The provenance of the BRSM is not so readily apparent. Thin section studies on a limited number of samples using detrital modal analysis (QFL) (i.e. assessing the proportions of quartz, feldspar and types of lithic fragments) show that the marine sandstones have a lithic component which is low in volcanic rock fragments suggesting that they are not derived directly from the magmatic arc (e.g. Dickinson 1985). These preliminary results are similar to those obtained from the "slope basin" sandstones of the Nias Island forearc sequences to the west of Sumatra (Moore 1979). Moore (op. cit) found that the Nias "slope basin" sandstones (Early Miocene to Pliocene), which were thought originally to have been derived directly from the magmatic arc to the east (i.e. Barisan Mountains), were too low in volcanic components and suggested that they were in fact probably derived from reworking of older pre-arc, sedimentary rocks exposed along the front of the magmatic arc.

With the seismic evidence strongly in favour of direct derivation of the Keutapang Formation sandstones from the arc it is hoped that future studies will determine whether QFL analysis has any real validity in the NSB basin. At present a lack of stratigraphically precisely located core from the Keutapang Formation has prevented further work on this problem. For the present our limited studies favour a different source for the BRSM sandstones than for the Keutapang Formation, possibly they were derived from the older Sunda Shield area to the east. These provenance studies are at an early stage in the NSB and it is hoped that as more samples become available it will become clear whether one or more sand sources are involved.

## V. FACTORS AFFECTING RESERVOIR QUALITY

### *V.1. General*

To be viable commercially a hydrocarbon reservoir must have adequate porosity and permeability. The core analysis studies outlined in the preceeding sections are in general aimed at assessing these poroperm characteristics i.e. their origins, distribution and connectivity, and also at assessing the factors which may affect a reservoir's quality either by enhancing or destroying its porosity and per meability. The ultimate aim is to enable more informed predictions concerning porosity-permeability trends across the reservoir as a whole to be made in order to maximise production from the reservoir.

### *V.2. The Besitang River Sand Member*

Oil production from the marine sandstones such as the BRSM is already substantial. The presence of authigenic chlorite cements has, however, considererably reduced the original porosity and permeabilities of the sandstones studied. Should improvement in production levels be necessary then its removal should be considered using acidization tehniques. There is a danger, however, that without adequate iron chelating agents (organic compounds which retard precipitation by complexing with metal ions), acids introduced into the reservoir while initially removing the chlorite would eventually reprecipitate iron- rich gels (ferric hydroxide) to block pore throats causing a fall in production levels to occur. Detailed core analyses help reservoir engineers to develop and use treatments which avoid such problems.

## VI. CONCLUSIONS

Many questions remain to be answered concerning the sedimentology and particularly the diagenesis of reservoir rocks, not only in the North Sumatra Basin but elsewhere in Indonesia. Despite a growing literature and extensive, though unfortunately largely unpublished, volume of research, for example, the source of the vast volumes of authigenic cements precipitated in the pore systems of reservoir rocks is by no means resolved. The amount of cement present in the reservoir requires vast quantities of ionic species to be donated to the pore fluid system. We still cannot be certain whether these donor species are redistributed by dissolution of grains within the reservoir or if they are supplied externally from reactions occurring in adjacent shale sequences. There is also still no certainty where the hydrocarbons present are derived from or how they are emplaced? These and many other fundamental questions still remain to be answered and Indonesian geologists, sedimentologists and geochemists, particularly at LEMIGAS, now have the chance to participate fully in the discussion and investigation of these and other topics.

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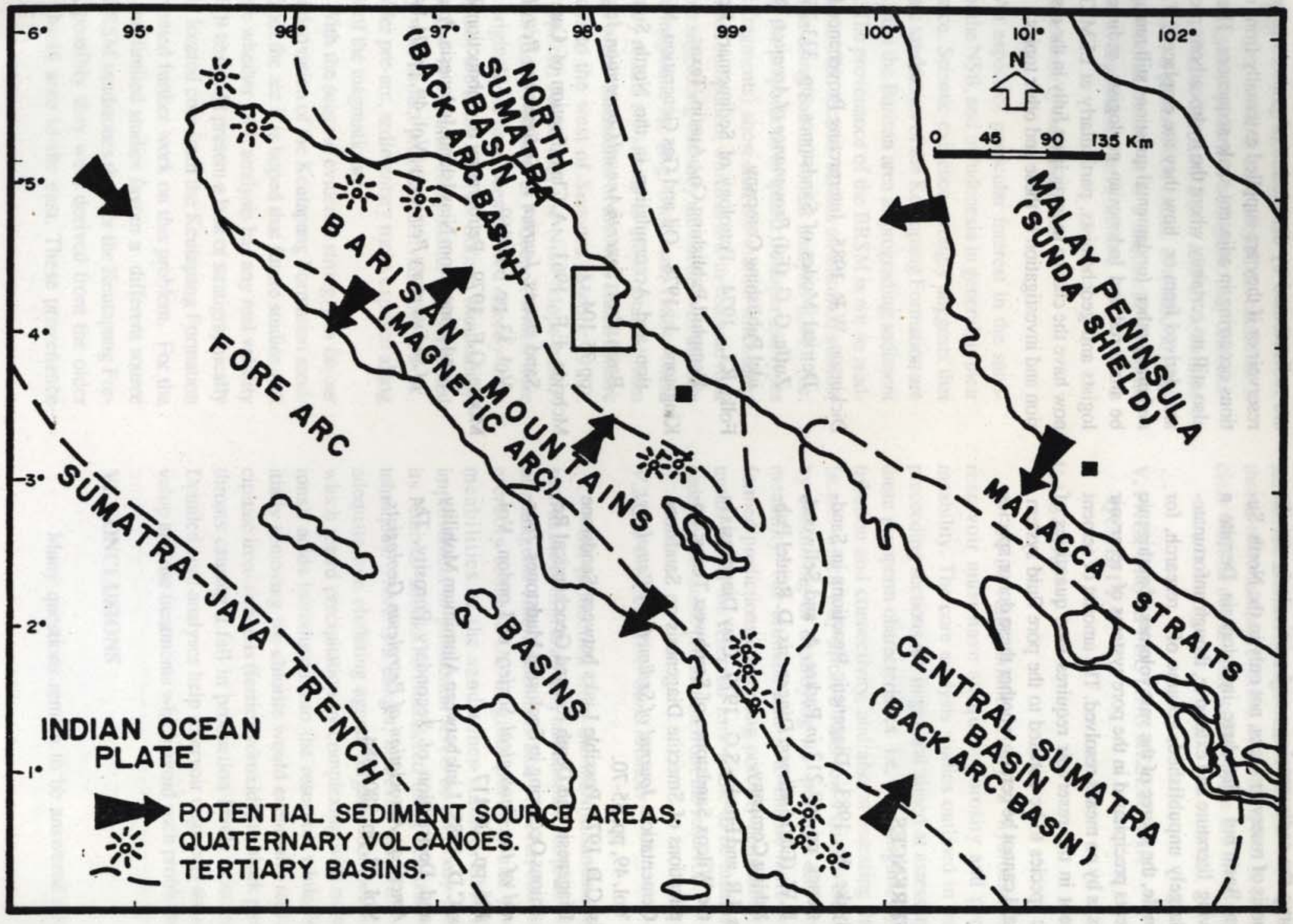


Figure 1. Sketch Map of the Northern Sumatra showing location of study area and main structure elements

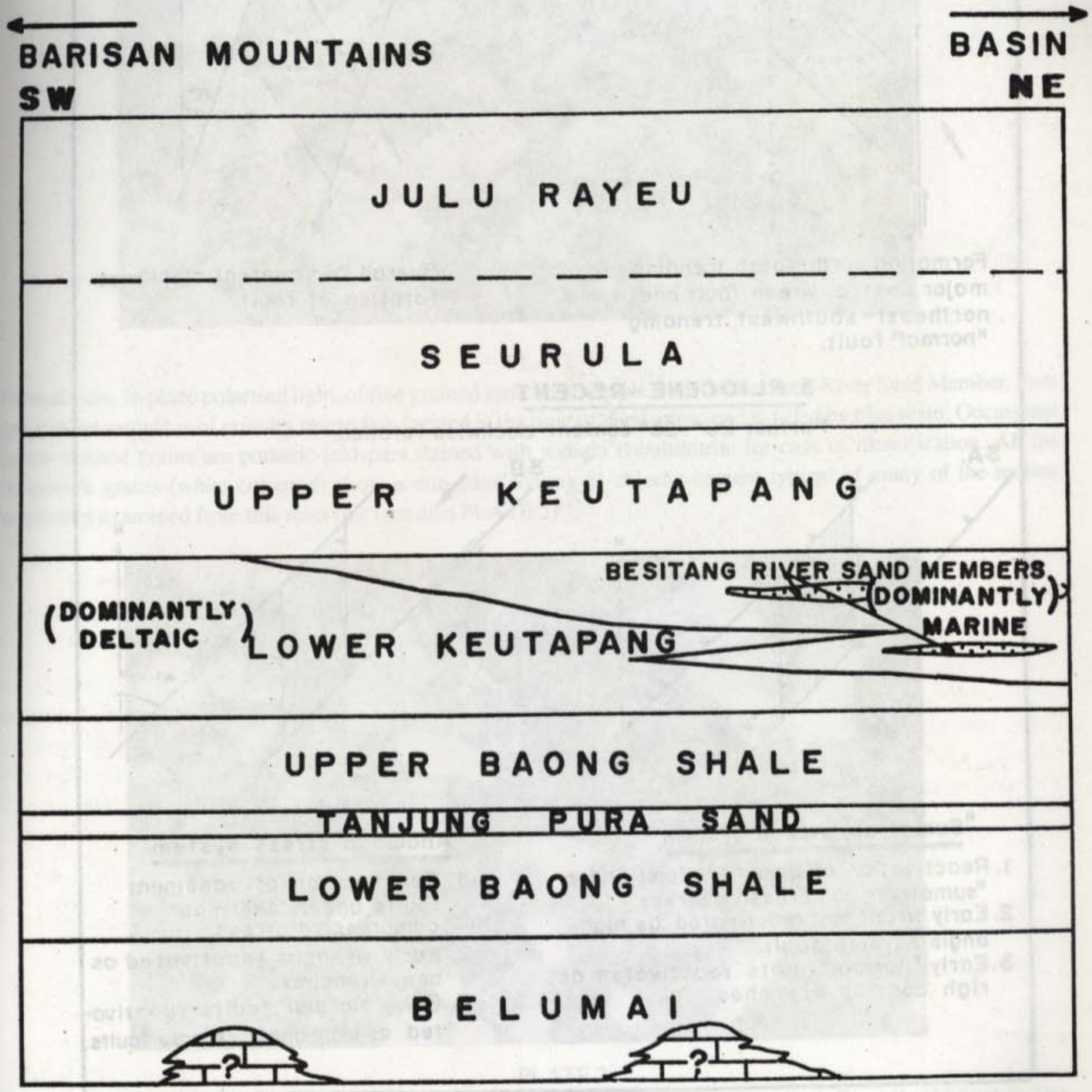
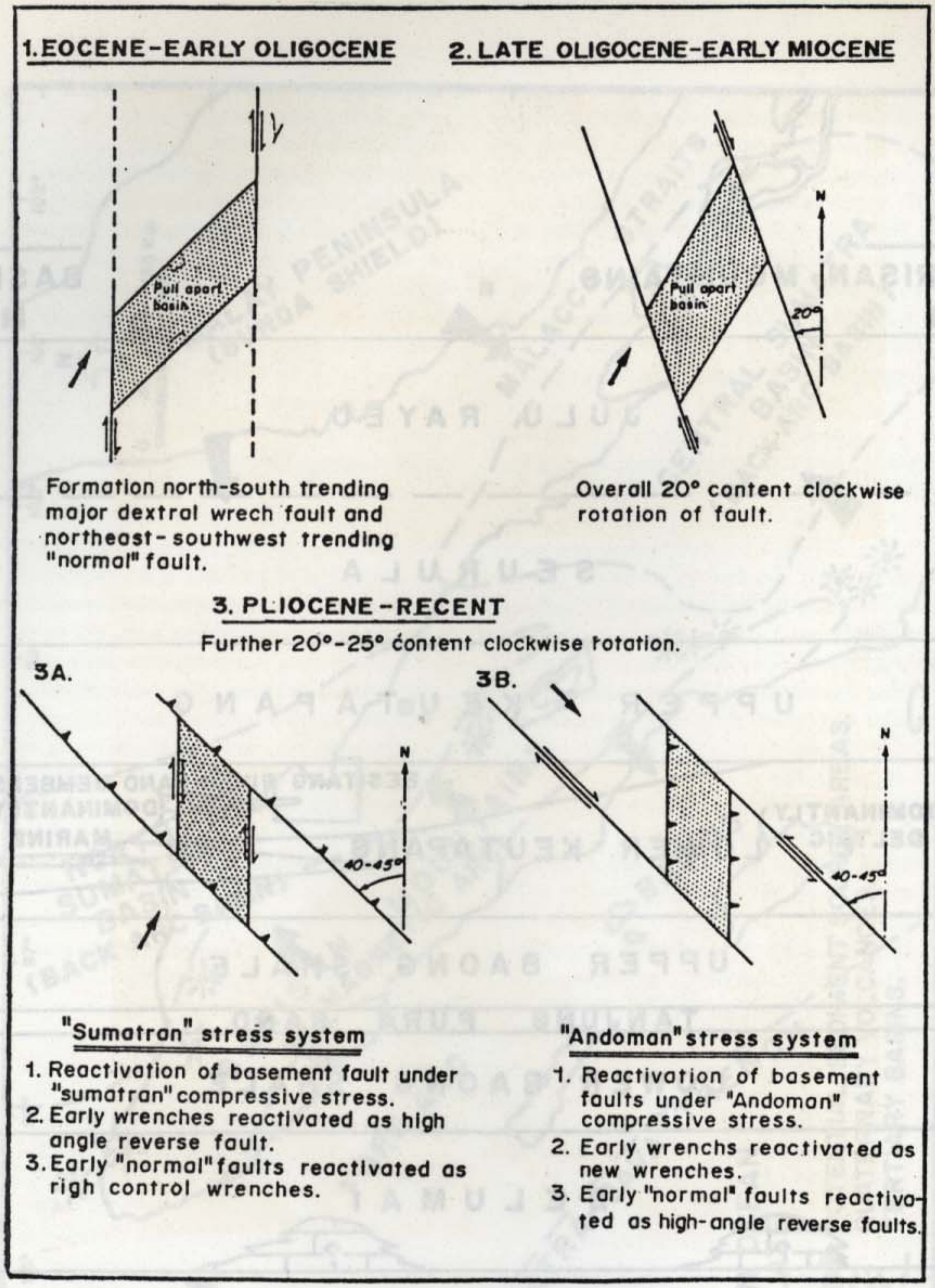


Figure 2
Tentative stratigraphic summary of the North Sumatra Basin (adapted from Kirby et al, 1987)



1. EOCENE-EARLY OLIGOCENE

Formation north-south trending major dextral wrech fault and northeast-southwest trending "normal" fault.

2. LATE OLIGOCENE-EARLY MIOCENE

Overall 20° content clockwise rotation of fault.

3. PLIOCENE-RECENT

Further 20°-25° content clockwise rotation.

3A.

"Sumatran" stress system

1. Reactivation of basement fault under "sumatran" compressive stress.
2. Early wrenches reactivated as high angle reverse fault.
3. Early "normal" faults reactivated as righ control wrenches.

3B.

"Andoman" stress system

1. Reactivation of basement faults under "Andoman" compressive stress.
2. Early wrenchs reactivated as new wrenches.
3. Early "normal" faults reactivated as high-angle reverse faults.

**Figure 3**
**Possible reactivation of faults during the Tertiary (Davies, 1984)**

PLATE 1

General view, in plane polarised light, of fine grained sandstone sample from the Besitang River Sand Member. Pore space in the sample is of primary origin (i.e. formed at the time of deposition) and is filled by blue resin. Occasional yellow stained grains are potassic-feldspars stained with sodium cobaltinitrite for ease of identification. All the framework grains (white coloured) show a thin dark coating of chlorite cement typical of many of the marine sandstones examined from this reservoir (see also PLATE 3)

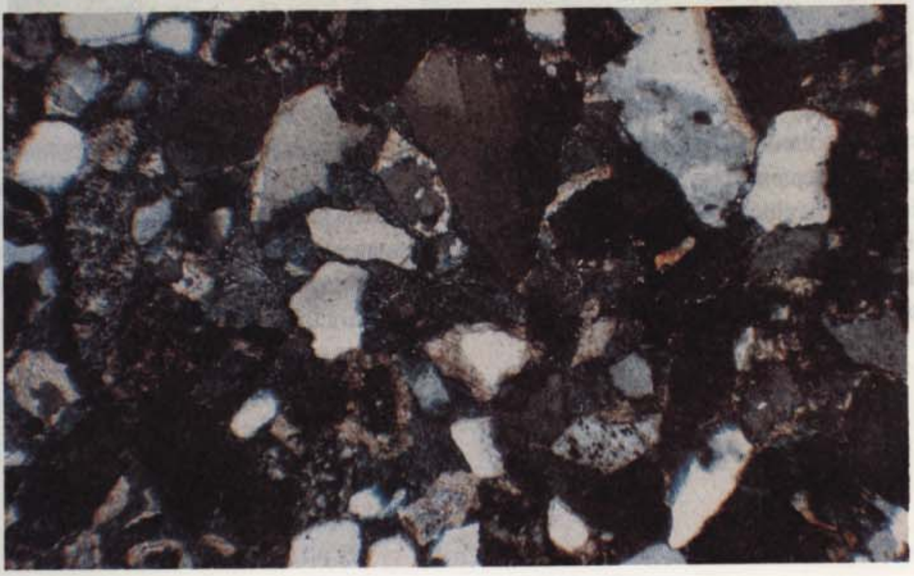


PLATE 2

General view, in cross polarised light, of fine grained sandstone sample from the Besitang River Sand Member. The sandstone is 'tight' i.e. has no porosity because pore space is filled by ferroan calcite cement stained blue for ease of identification. Note that no chlorite grain coatings are developed on the framework grains.

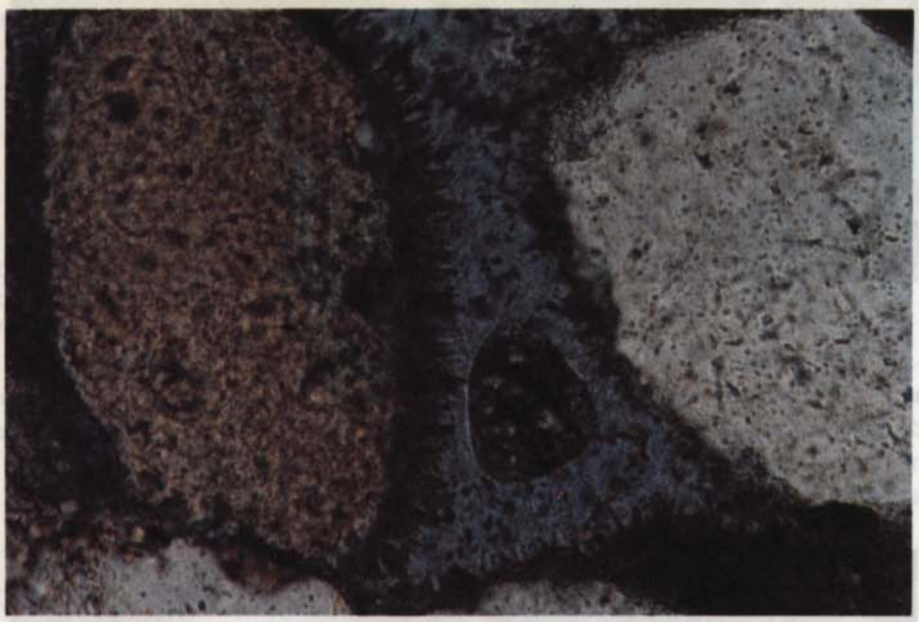


PLATE 3

This view, in plane polarised light, shows two framework grains glauconite (left-green coloured) and quartz (right-white coloured) separated by blue resin-filled pore space. The pore space is reduced by the growth of needle-like crystals of authigenic chlorite cement which are best developed on the glauconite grain in this view, but generally coat all grains in the sandstones (see PLATE 1). The chlorite crystals have grown after deposition (i.e. are diagenetic minerals) in situ because their delicate structure would not survive transport of the grains. Authigenic cements such as chlorite cause a reduction in reservoir quality by blocking or restricting porosity and permeability channels in a rock.

PLATE 4

This view, in cross-polarised light, shows a yellow-stained potassic- feldspar and several white quartz grains surrounding a pore space which is filled by ferroan carbonate cement (note the well developed cleavage lines in the cement). Each framework grain has a thin chlorite coating. From this view we are able to determine that the carbonate cement was precipitated later than the chlorite grain coatings (in the diagenetic history of this sample the carbonate cements are said to post-date the chlorite cements). By using this kind of evidence it is possible to determine the sequence of cementation (cement stratigraphy) or paragenesis of the sandstones.

PLATE 5

This view, in plane polarised light, shows a large sodic-feldspar framework grain which has been corroded along its cleavage planes. The resulting 'holes' in the grain are filled by blue stained resin. This type of corrosion forms secondary porosity by removing part or whole grains from the sandstone. In the Besitang River Sands the most unstable grains are the feldspars, rock fragments and glauconites which often shown signs of corrosion. If secondary porosity such as this is well developed it can significantly improve the quality (i.e. porosity and permeability) of a reservoir.

PLATE 6

This view, in plane-polarised light, shows a pore space (blue resin-filled) in which there is a remnant chlorite grain coating. The original framework grain, around which the chlorite coating developed, has been almost completely removed by corrosion leaving only a large secondary pore space and the remnant chlorite coating.

PLATE 7

This view, in plane polarised light, illustrates the complexities of diagenesis in the Besting River sandstones. The right side of the photo shows the pink-stained calcite test of a planktonic foraminifera. Within the chambers of this test green coloured glauconite has been precipitated, probably quite early in diagenesis. The left side of the view shows a severely corroded skeletal grain of sodic feldspar in which the holes have been filled by dark blue ferroan calcite cement. The skeletal grain also has a chlorite coating and the whole sample is cemented by slightly ferroan carbonate cement. The only porosity apparent is the blue resin-filled secondary pore along the lower edge of the photo. To unravel such a complex cement stratigraphy many thin sections need to be studied. This type of diagenesis raises many questions about the fluids that percolate or are trapped in a reservoir rock. For example in this section we see a silicate grain (sodic feldspar) which is severely corroded yet the calcitic foraminifera test is untouched. Alternatively we have precipitated cements of chlorite and ferroan calcite filling pore spaces. Clearly fluids of widely differing acidity/alkalinity have penetrated this rock during its diagenesis some corroding grains others precipitating new mineral cements.

PLATE 8

In this view, in plane polarised light, the effects of physical compaction on the fabric of the sandstones is apparent. Physical compaction of a sediment begins soon after deposition and continues into deep burial. In this example repacking of the rock fabric has resulted in the squeezing of a ductile glauconite grain between more rigid quartz (white) and feldspar (yellow) grains. Other grains which show the effects of physical compaction in these sandstones include micas and brittle bioclastic debris. In the example illustrated chlorite cements have coated the strain-free parts of the glauconite.

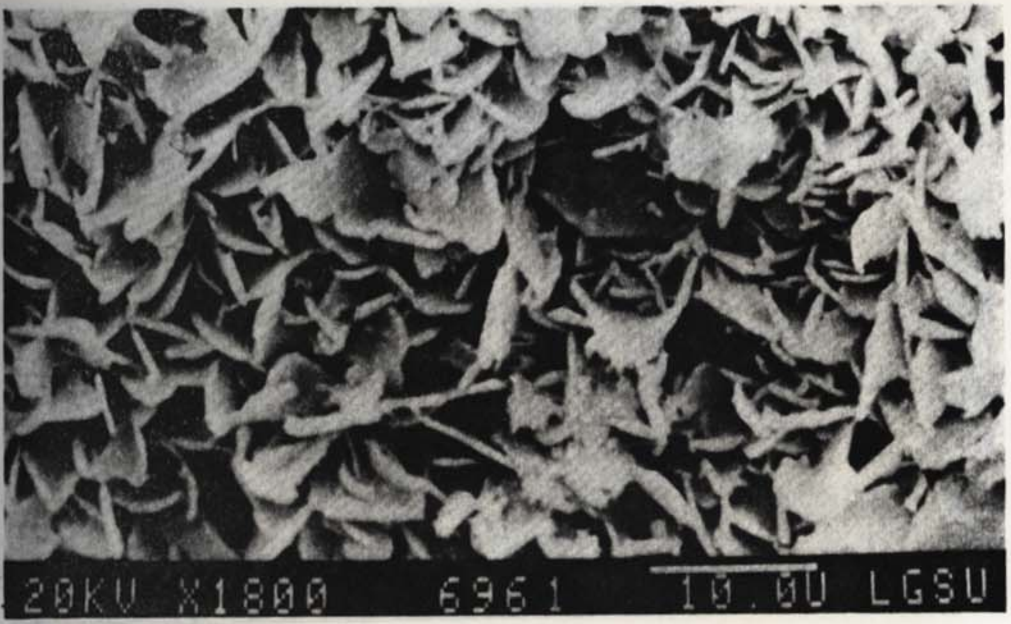


PLATE 9

Close-up of platy chlorite crystals forming typical "box-of-cards" structure.

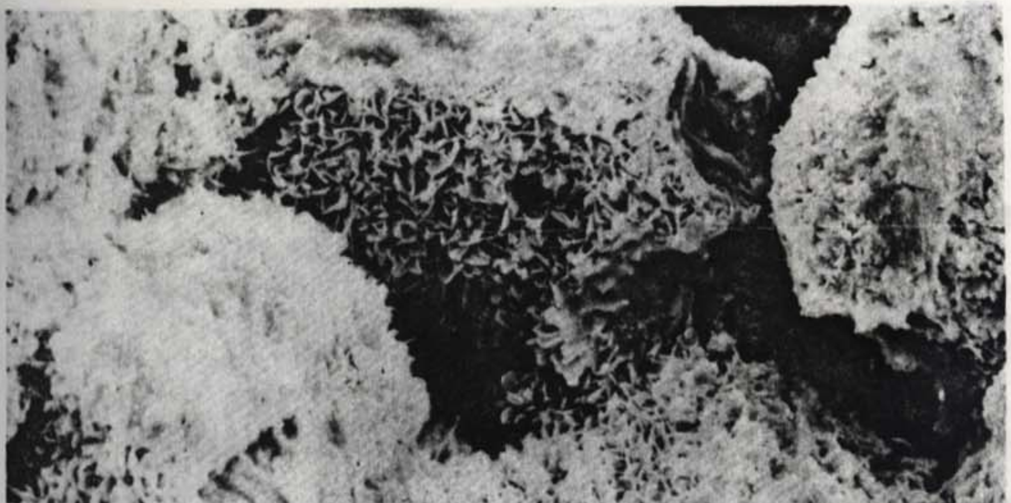


PLATE 10

Grain coating authigenic chlorite cement and primary pore space.

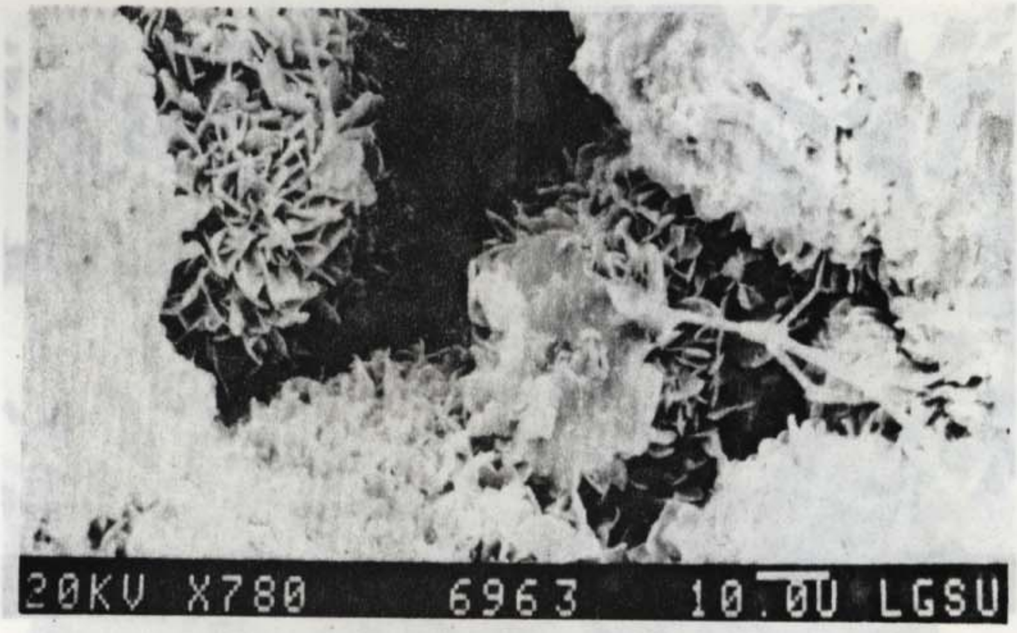


PLATE 11
Primary pore space reduced by authigenic chlorite cement. Authigenic illite fibre in lower right corner.

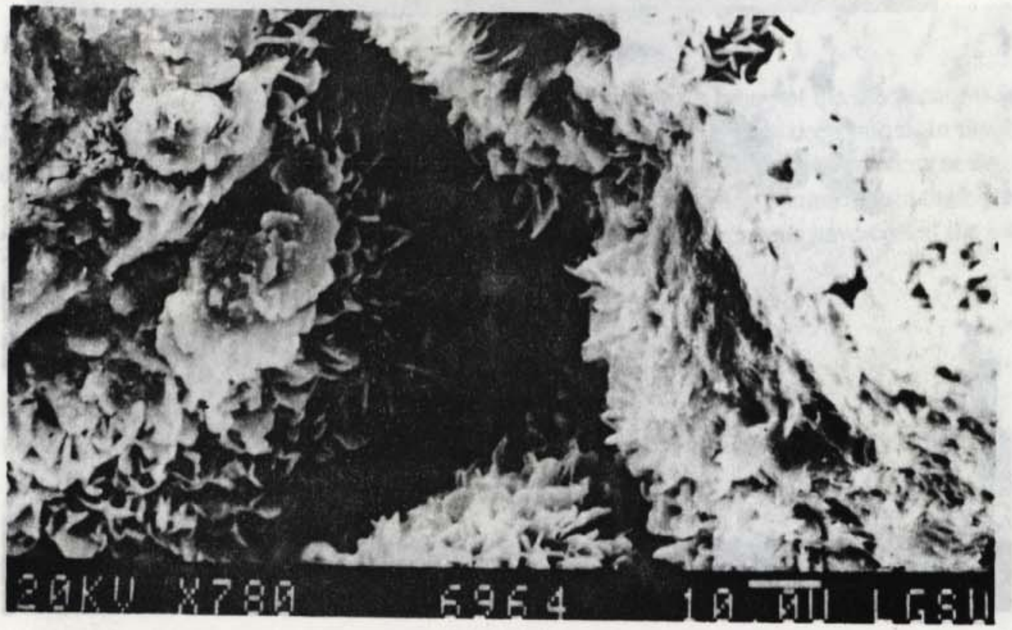


PLATE 12
Authigenic chlorite coatings usually reach up to 10 microns in thickness. In these views fracturing of the sample during preparation clearly shows the host framework grains with their chlorite fringes partially removed.

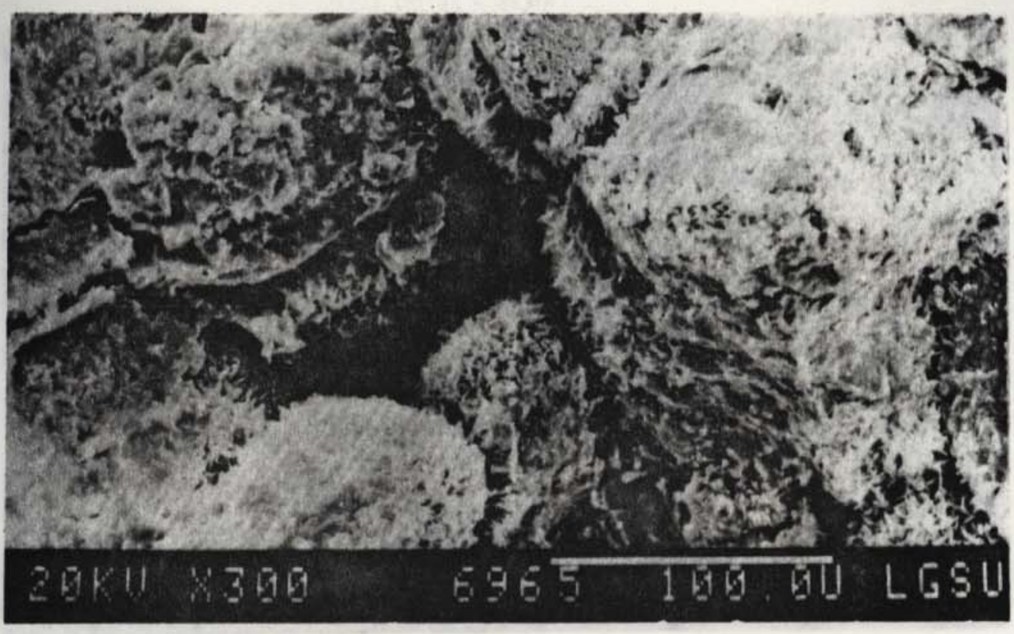


PLATE 13
General view showing the pervasive nature of the chlorite cements.

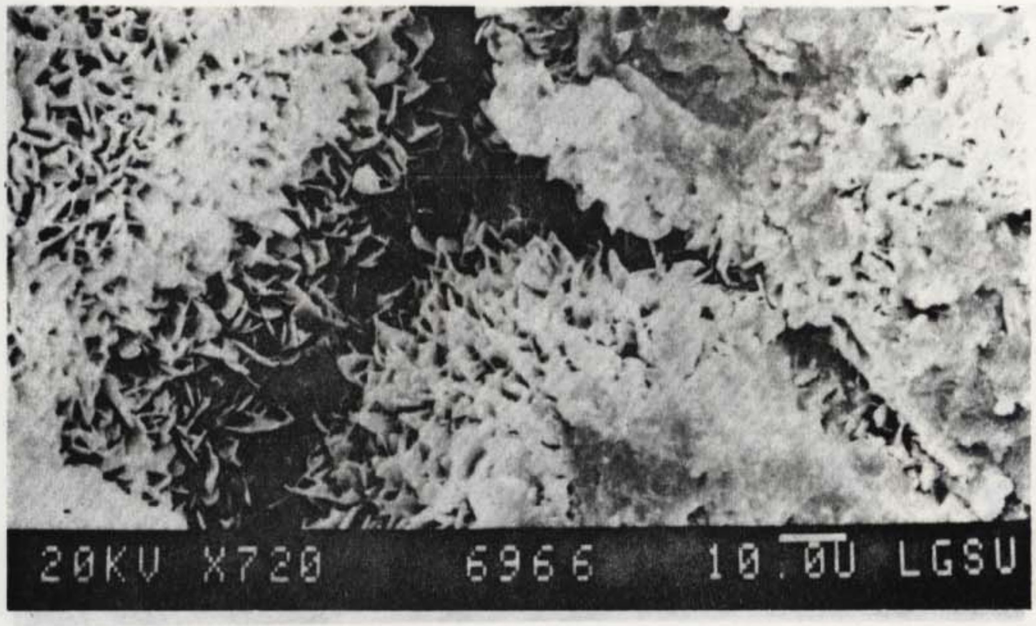


PLATE 14
Close-up view of the platy chlorite fringing cements.

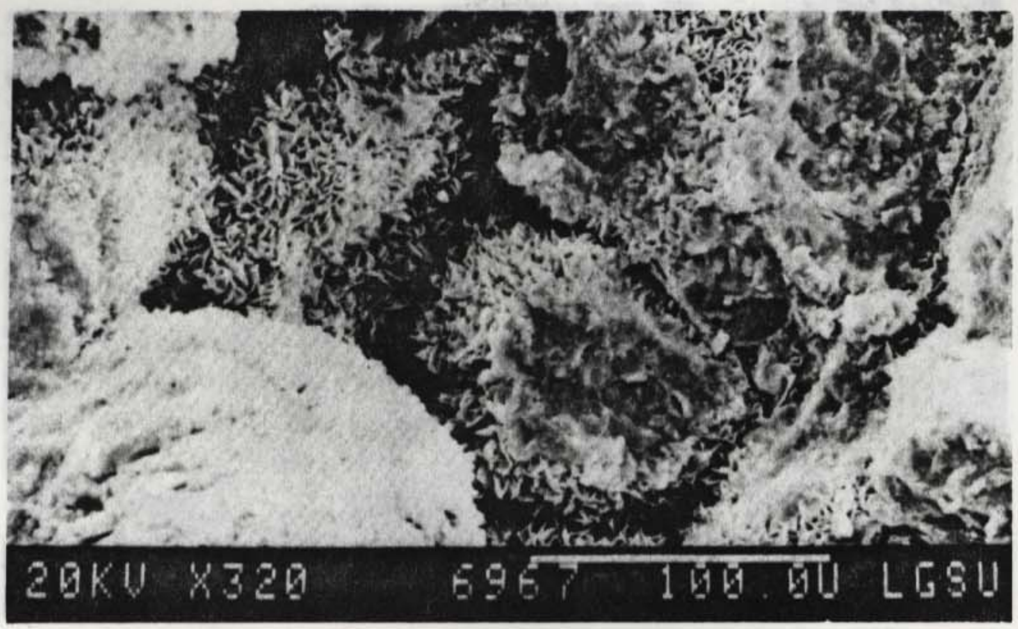


PLATE 15

The authigenic chlorite cements have reduced primary porosity by up to 55%, sufficient porosity remains however to make the unit a promising reservoir prospect.

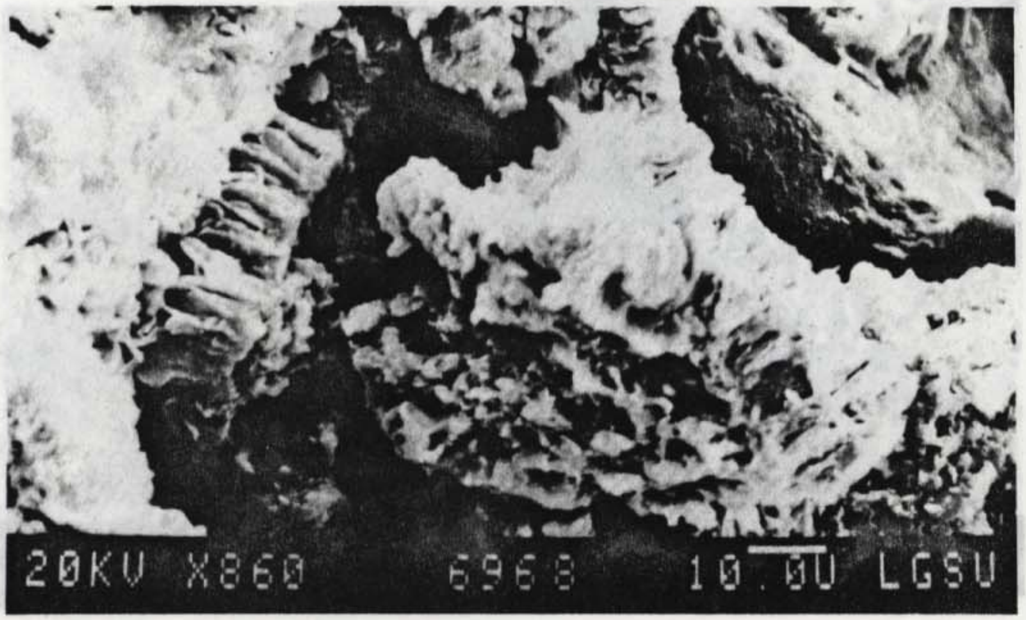


PLATE 16

Fracturing of the sample during preparation clearly shows the chlorite cements precipitated edge-on to the host grain.

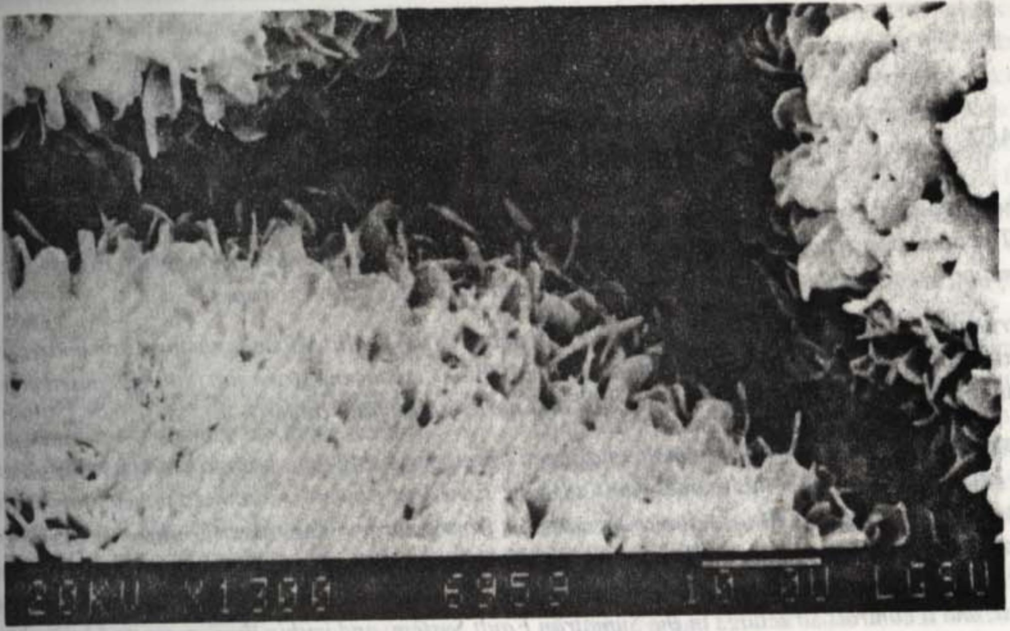


PLATE 17

Close-up of primary pore space partially occluded by authigenic chlorite plates which coat the framework grains. Individual chlorite plates are precipitated edge-on to the host grain.

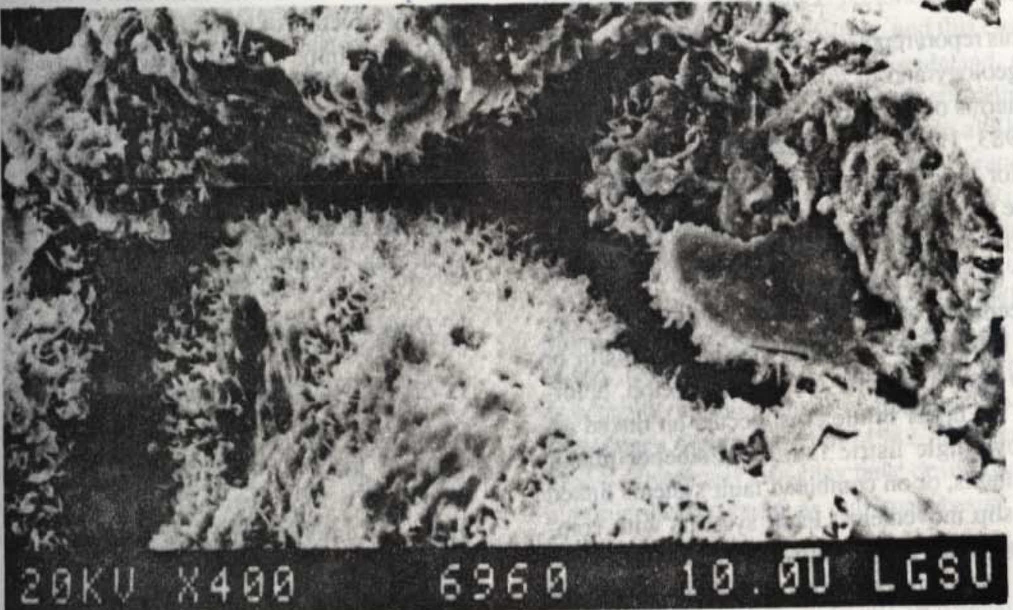


PLATE 18

Primary pore space within these sandstones is partially occluded by pervasive authigenic grain coating chlorite cements and by less well developed euhedral quartz overgrowths (top left grain).